THE UNIVERSITY OF ALBERTA

# A STUDY OF THE EFFECT OF GASOLINE AND PROPANE FUELS ON ENGINE WEAR BY USING RADIOACTIVE TRACERS

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "A Study of the Effect of Gasoline and Propane Fuels on Engine Wear by Using Radioactive Tracer" submitted by Meng Young Kuo in partial fulfilment of the requirements for the degree of Master of Science.

## ABSTRACT

The objective of this investigation was to make a comparison of wear effects between gasoline and propane under various operating conditions so as to determine the optimum operating conditions for each fuel for minimum engine wear.

The wear test was carried out by means of radiotracer techniques. The detailed procedure for measuring wear rate by using radioactive tracers are described. The radioactive constituents are listed and safety precautions mentioned.

The results discussed were classified under three broad divisions: The effect on engine wear of:

(1) Lubricating oil temperature - It was found that the optimum lubricating oil temperature for both gasoline and propane is 150°F for minimum wear under the conditions of the test.

(2) Air-fuel ratio - It was found that the wear rate increased considerably when the mixture was lean.

(3) Engine load - It was found that the wear rate affected by both gasoline and propane increased markedly as the horsepower was reduced.

The results are presented in the form of graphs.

It is hoped that this study might contribute somewhat to the knowledge of methods for reducing engine wear.

# ACKNOWLEDGMENT

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# PART I

## INTRODUCTION

The service life of internal combustion engines is affected by engine wear which is principally piston ring and cylinder wall wear. Severe engine wear causes not only considerable reduction in horsepower but also excessive oil consumption. (11,16,23,28,29) The engine performance will therefore be drastically impaired and the engine will deteriorate. (5,32) In order to prolong engine life, there is a need to find the major causes of this wear and ways of reducing it.

In determining ways by which wear of piston rings and cylinder walls can be reduced, many research projects have been carried out during recent years. This research was generally undertaken by using different grades of gasoline or lubrication oil under various conditions which could affect piston ring and cylinder wear. The engine operating variables have been different jacket temperatures, oil temperatures, engine load and speed, etc. From the reports of previous researches, however, it seems that little work has been done on the comparative wear rate test between gasoline and propane fuels under various operating conditions. This in spite of the fact that there is a possibility of an increased use and impending importance of propane as an engine fuel.

The objective of this thesis is to find the effect of propane on engine wear comparing it with gasoline under different oil temperatures, different air fuel ratios and different engine loads so as to determine the optimum operating conditions for minimum engine wear.

## PART II

## THEORY OF ENGINE WEAR

There are a number of factors or conditions which may readily contribute to accelerated wear and greatly shortened engine life. Because of the fundamental importance of wear, extensive research has been devoted to its causes. Investigators have found that engine wear may result from four basic causes:

(1) Corrosion (6,7,23,27) - Corrosion is generally recognized as the chief cause of engine wear. It is the chemical attack on metal surface by moisture and acidic constituents originating from the combustion processes. The constituents such as carbon dioxides, sulfur oxides, on condensing or reacting with water, form acidic and potentially corrosive materials which can cause extreme engine wear. The corrosive tests indicate that factors that could affect corrosive wear are as follows:-

(a) Jacket temperature (2,6,7,11,23) - Jacket temperature has a significant effect on corrosive wear. As the jacket temperature is below the dew point (150$^{o}$F) of the combustion gases, the moisture and acidic products may readily condense on the ring surfaces, causing corrosive attack which ultimately results in a loss of metal. H.R. Jackson (12) indicated that approximately 45% of engine wear is due to low temperature corrosion from cold starting. Since jacket temperatures are so vitally related to corrosion, any means of maintaining high jacket temperatures during operation are of great value in minimizing wear.

(b) Oil film thickness (23) - The film of oil between the surfaces of cylinder wall and piston ring will serve as a barrier to the penetration of acidic molecules to the metal surface. If the oil film is not thick enough, piston rings will be subject to unavoidable corrosive wear.

(c) Oil alkalinity (11,23) - Corrosive wear can be reduced by using an alkaline oil additive as it can neutralize the acids before they reach the metal.

(2) Abrasion (6,7,19,23,27) - Abrasion is friction wear caused by foreign particles between the rubbing surfaces. The foreign particles such as dust, dirt and other solids may find their way either through the induction system to the cylinder or through the ventilation system into the crankcase. The best protection against this type of wear is, of course, efficient air cleaners and oil filters and adequate sealing of the engine. The contamination of iron particles in the lubrication oil, resulting from wear of piston rings and cylinder walls also contributes to additional wear. These iron particles act as an abrasive material. Frequent oil changes may minimize the sources of this type of wear.

(3) Friction (6,19,23,27) - Wear by friction is caused by metal to metal contact due to inadequate lubrication. As the piston rings are sliding over the cylinder surface, the surfaces actually will be in close contact at relatively few points due to irregularities of the surface. Irregularities on each surface will cut or deform the other surface at the points of contact where the oil film is extremely thin. This action will lead to a smoothing of the surface, an increase in the area of actual contact, and an improvement in the load carrying ability of the surface. During the break-in period this type of wear

is desirable, but after the surfaces fit properly it should be brought to a minimum. Factors affecting the friction wear are as follows:

(a) Surface condition - If both surfaces are well finished, friction wear may be reduced to a minimum. If either surface has irregularities which penetrate the oil film, wear can be expected to continue.

(b) Material properties - Hardness of the material affects the depth of surface penetration by irregularities and hence the amount of cutting.

(c) Oil viscosity - One of the chief functions of lubrication oil is to prevent friction wear by interposing fluid oil films between rubbing surfaces to preclude metal-to-metal contact and consequent wear. The oil viscosity has an effect since it helps to determine how close the two surfaces will approach each other or how small an irregularity will penetrate the oil film and cut the other surface. Use of oil of adequate viscosity and of sufficient heavy grade for engine lubrication will prevent excessive friction wear.

(4) Scuffing (10,19,23) - Scuffing wear is caused by the welding of points on the two surfaces and subsequent tearing away of the welded junctions. Once the surface has been roughened by scuffing, a considerable amount of friction wear would be expected to occur. Factors affecting scuffing are as follows.

(a) Surface condition - High surface temperatures and clean metallic contact are the main factors that cause scuffing. If there is a layer of oil film which is thick enough existing between the two rubbing metal surfaces, the two surfaces will be separated and thus the trend of scuffing eliminated. Scuffing is serious during break-in sicne there are high temperatures and extremely thin oil film between the surfaces. Once the surface is roughened by scuffing, wear rates will be high because of friction wear.

(b) Material properties - The exact properties that make a material resistant to scuffing have not been fully determined. Metal coatings and finishes of various types have been used very effectively in preventing scuffing. A common rule has been not to use the same material for both parts, cast iron rings however are used very successfully in cast-iron cylinders.

(c) Oil viscosity - Scuffing can be prevented by higher viscosity lubricants which provide a film that is more difficult to penetrate.

(d) Other factors - High temperatures, high pressures, and rubbing velocities are also important factors of scuffing.

Note: Most of the scuffing starts near the top of the bore where the temperature is highest, the lubrication poorest and the piston speed the lowest.

## PART III

### EFFECT OF GASOLINE AND PROPANE ON ENGINE WEAR

The types of wear on which gasoline and propane fuel have a great effect under cold start-up conditions are friction and corrosion wear (27).

(a) Engine wear affected by gasoline

i. Friction - When engine is started in cold weather, the unevaporated gasoline will not only wash off the oil film on the cylinder walls but also dilute the oil in crankcase. Both of these conditions are causes of friction wear.

ii. Corrosion - There are many impurities contained in gasoline. The chief one is sulfur. When condensation occurs on cylinder walls during cold weather starting, sulphuric acid is formed. This acid-forming substance will cause serious corrosion.

(b) Engine wear affected by propane

i. Friction - As the propane is a dry gas, it is unlike gasoline which will provide some liquid protection when the residual oil film has been burned or scraped off by the oil ring. The friction wear rate affected by propane is more serious than gasoline.

ii. Corrosion - Owing to the dry operating condition of a propane engine during the interval between starting and effective oil circulation, there are more possibilities of blow-by occurring through the ring gaps, between the ring face and the bore. It was found that the condensed blow-by

is very acidic. A pH of about 2 has been found (13). Since blow-by is the source of corrosive material, the more blow-by in the propane engine, the more corrosive material will be accumulated in the lubrication oil with the result of increasing corrosive wear.

The processes by which wear of rings and cylinder walls occurs in engines are complex. From the above theories, it is difficult to evaluate which fuel will result in less engine wear. Therefore it was decided that an attempt should be made to solve the problem by means of comparative tests.

## PART IV

## METHODS OF MEASURING ENGINE WEAR

There are three methods used to determine engine wear:

(1) Physical measurement (4,5,6,17,21,22,23,26,29)

(A) Procedure:

(a) To have the parts such as piston rings, cylinder liners carefully weighed and measured.

(b) To assemble the test engine with parts measured by weight or dimension and to run the engine under the selected operating conditions for an extended period.

(c) To dismantle the engine for inspection which includes visual observation and rating, measuring, weighing and photographing.

(d) By subtracting the final measurements from the initial measurements to get the amount of wear that has occurred (either change in weight or dimensions).

(B) Disadvantages

(a) Relatively long runs (more than 500 hours) are necessary to produce significant results.

(b) The intermediate disassembly of the engine sometimes causes erratic results because of inability to reassemble the test engine in exactly the same manner each time.

(c) There is a lack of sensitivity so it cannot be used for study of transient effects.

(d) Results are influenced by the surface finish, material composition, hardness and in mechanical fit in successive tests. Those factors can make large enough differences in wear rates to spoil the reproducibility to some extent.

(2) Chemical analysis (4,6,17,22,23,26,29)

This is a less popular method which measures engine wear by chemical analysis for iron worn from the moving parts of the engine. The wear products enter the film of lubricating oil between the moving parts and drain down into the crankcase. This wear test method is based on the increase in iron content of the lubricating oil. In this method, the engine does not need to be dismantled to obtain the measurement. Thus mechanical factors such as surface finish, break-in, or distortion can be practically eliminated. This method owes its precision to the fact that as little as 7 millionths of an inch of change in cylinder diameter can be detected. However, this method also has certain disadvantages:

(a) Comparatively long runs are required. The shortest operating period for measurable wear determination with the iron analysis method is about 25 to 50 hours.

(b) The sensitivity is low.

(c) The iron may not have come only from the part of interest so the source of the iron in the lubricating oil is not always definitely established.

(3) Radiotracer method (2,4,5,6,17,21,22,23,26,29,35)

This is a most recently developed method for measuring engine wear. In this method, the top, or other, piston ring is made radioactive by neutron bombardment in a nuclear reactor and then installed in the test engine. As the ring wears during the engine operation, the wear debris is carried in suspension by the lubricating oil.

Wear is determined by a continuous sampling procedure in which the lubricating oil containing the radioactive wear debris is circulated around a detector (a $\gamma$ sensitive Geiger-Mueller counter or a Scintillation Crystal counter) which is connected to a rate meter and then to a chart recorder.

The electrical pulses from the detector are counted by a ratemeter and recorded continuously on a chart recorder. The result is a continuous curve relating count rate against time plotted on the chart. The slope of this curve is directly proportional to the rate of wear of the irradiated ring.

The absolute wear rate in milligrams of iron per hour is calculated from the count rate slope, specific activity of the ring on the date of the test, and the average volume of lubricating oil in the crankcase during the run.

A more detailed description of these procedures and calculations is given later in this report.

This new method of measuring engine wear overcomes all the inconveninece common in the conventional physical and chemical methods. The advantages of this method are as follows:

(a) The method has an extreme sensitivity which is several hundred times more than the iron analysis method. A few millionths of a gram of iron debris in the crankcase or a tenth of a millionth of an inch wear out from the metal surface can be detected and measured.

(b) The wear rate is continuously recorded as shown by a curve so that the effect of a large number of operating variables can be measured in a short period of time, measurements that might have required years to make by direct physical methods.

(c) The effects of transitory phenomenon, such as the effect of various fuels or oils on wear rate, can be observed. This would be impossible to detect by any other method.

(d) The disassembly of the engine after each test to obtain the wear data is eliminated. So the mechanical factors will not influence wear values. On the other hand, it offers great savings in time and labour such as careful cleaning and weighing involved in the weight loss method.

(e) By this method, there is no question as to where the iron in the lubricating oil come from. It can only come from the part which has been irradiated.

Owing to the great advantages mentioned above, the radiotracer method was thus chosen as the most precise and convenient means for obtaining the wear measurements in this test.

## PART V

## EXPERIMENTAL EQUIPMENT

(1) Engine and accessories

(A) Engine - The engine used in the test is a single cylinder 4-cycle, overhead valve, water-cooled "ASTM-CFR" gasoline engine with 3.25 inch bore by 4.5 inch stroke and with room air supplied for combustion. (Figure 1)

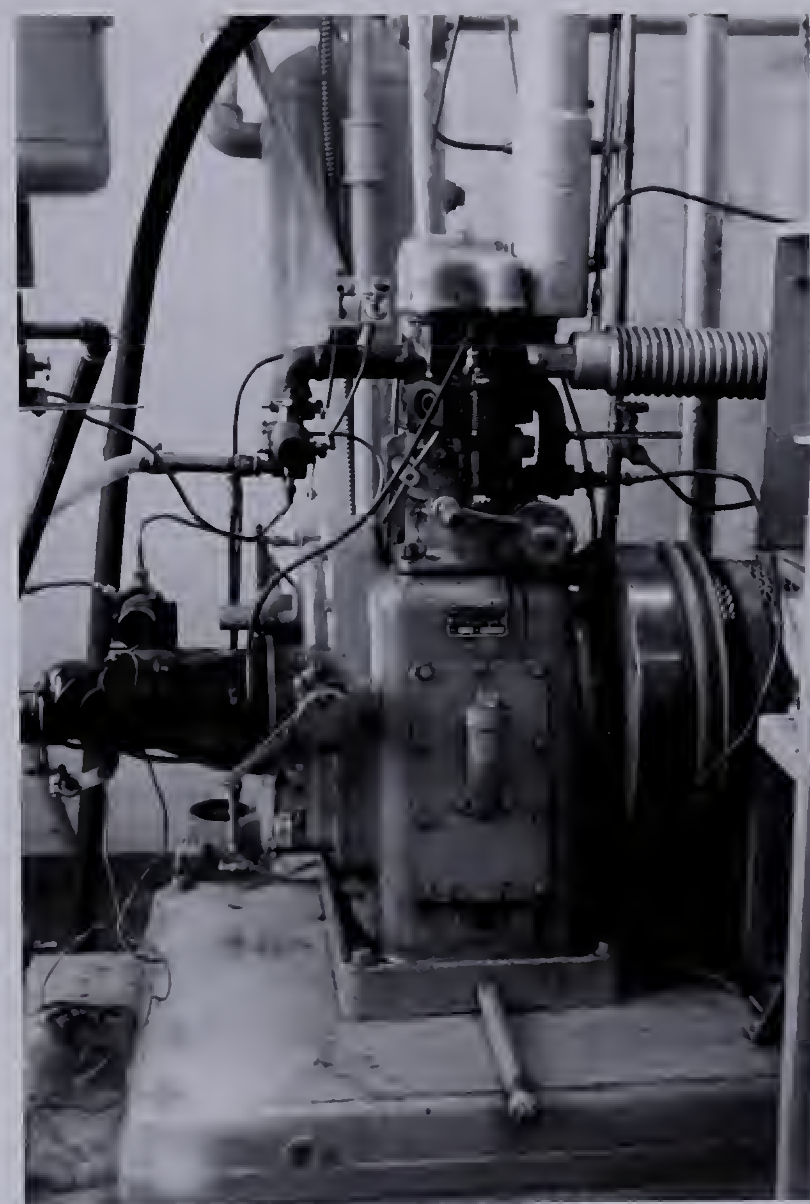


Figure 1. Testing Engine

(B) Accessories

(a) Dynamometer - It is a 25 hp alternating current cradled dynamometer coupled directly to the engine by two flexible couplings. It is used to start the engine and absorb the power developed by the engine. Power is measured by the pull exerted on a springless dial scale.

(b) Cooling system - The cooling system is equipped with a coolant return pipe and a water-cooled condenser to provide sufficient cooling capacity. The cooling water is used to cool the cylinder, the exhaust manifold and the lubrication oil.

(c) Lubricating system - On the CFR engine crankcase a gear type pump is mounted externally, with external connecting line leading from the bottom of the crankcase. Lubricating oil is circulated through the counting equipment by means of the oil pump. There is a thermometer used to record oil temperature during the test run and a pressure guage on the panel shows oil pressure.

(d) Fuel supply system - When gasoline is used as the engine fuel, an electrical pump is used to pump the fuel to the carburetor. When the engine is converted to propane fuel engine, a fuel pressure regulator and spud-in propane assembly are used. The fuel pressure regulator used in this experiment is the Ensign Standard Model "R" Butane Regulating Unit. (Figure 2)

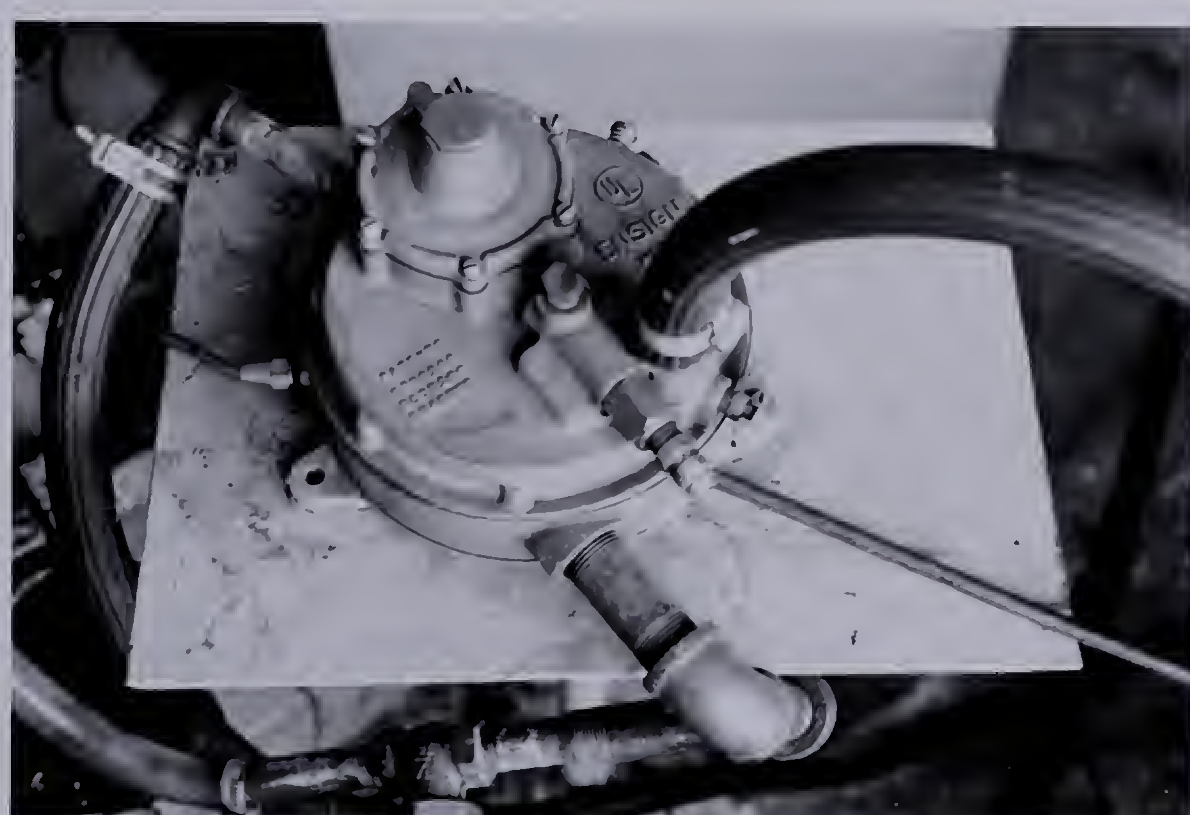


Figure 2. Propane Pressure Regulator

(2) Counting equipment - The counting equipment includes a counting ratemeter, a scintillation detector, and a paper chart recorder. (Figure 3)

Figure 3. Counting Equipment

(a) Count ratemeter - This is the Nuclear-Chicago Analytical count ratemeter, Model 1620 B which is used to convert random pulses received from an external radiation detector into an average count rate. By using this instrument, the counting rate is presented on a panel meter and an optional external recorder. The instrument also provides an aural indication of the average counting rate in the form of an audio tone. The pitch of the tone changes distinctly for minute changes in the counting rate.

(b) Scintillation detector - This is the Nuclear-Chicago well scintillation detector, DS-202(V) which is the $\gamma$ sensitive instrument designed to provide highest resolution and efficiency in spectrometry applications. In this detector, there is a 2 inch crystal with a 1 1/2 inch deep and 21/32 inch diameter well that will accomodate 1/2 inch diameter test tubes or sample bottles. This detector is equipped with two-piece lead shield which offers approximately 2 inches of lead above and around the sides of the detector. The top of the shield has a removable plug to allow large bottles or sample pans to be placed directly on top of the crystal.

(c) Paper chart recorder - This is the Nuclear-Chicago Model R1000 A Recitilinear Recording Milliammeter which is a graphic d-c milliameter designed for laboratory and field use. It has a rolling chart paper and an ink-pen instrument. The speed of rolling chart paper is controlled by a set of chart speed change gears. Ten chart speeds are available, using the combination of gear pairs and the chart speed switch.

## PART VI

## WEAR RATE MEASUREMENT BY USING THE SCINTILLATION DETECTOR (2,4,5,8,26)

The measurement of the piston ring wear rate can be continuously made by using a scintillation detector which contains a sodium iodide crystal and a photomultiplier tube. This scintillation detector is connected to a ratemeter and a chart recorder. A schematic diagram of this measurement system is shown in Figure 4.

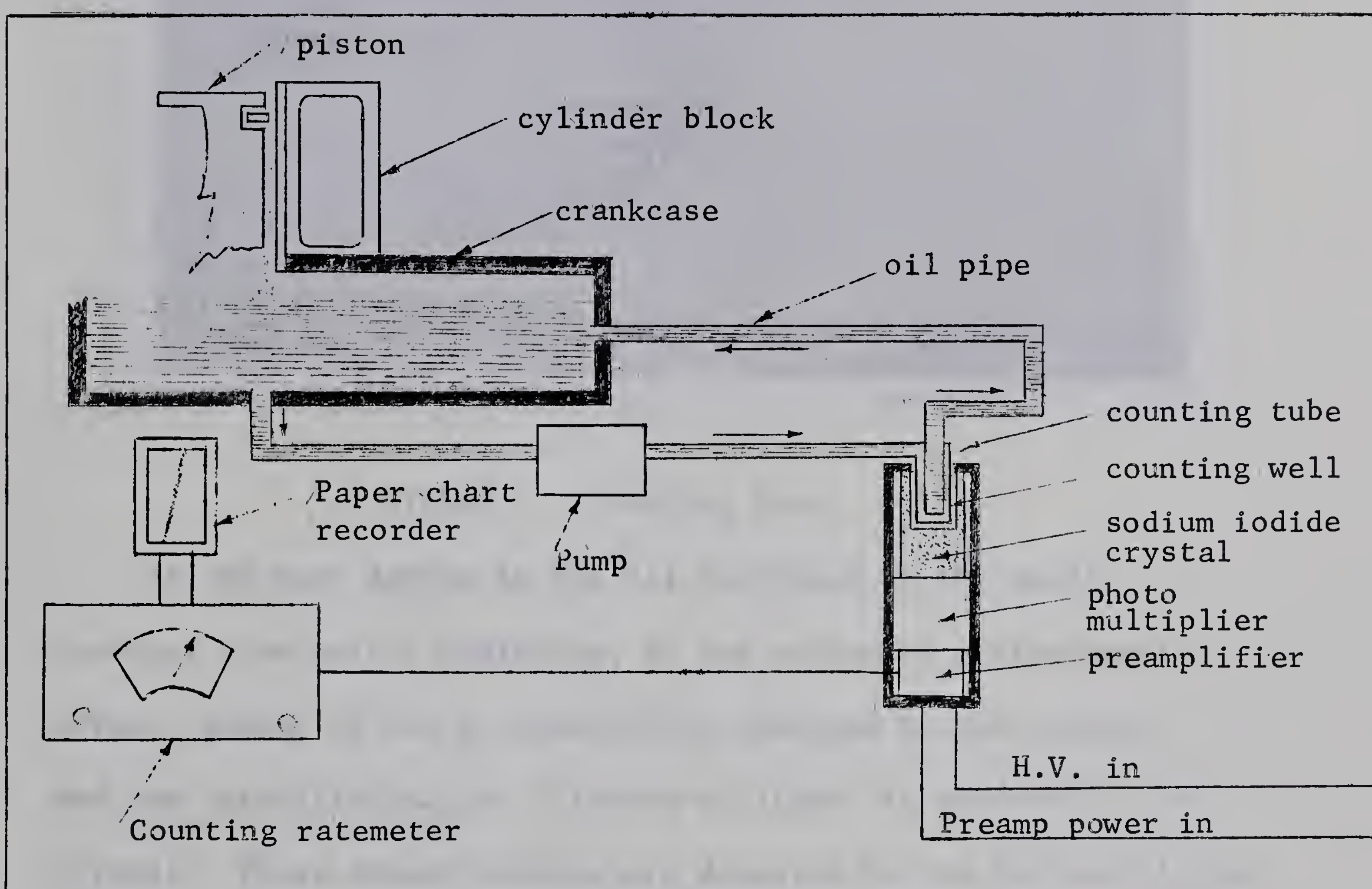



Figure 4. Wear Rate Measurement System

As ring wear occurs, the small radioactive wear particles flow down along the cylinder wall and accumulate in the crankcase. The lubricating oil is pumped continuously from the crankcase by means of a pump situated in an oil line leading from the bottom of the crankcase through a small counting tube and then returned to the crankcase.

The small counting tube is made of brass and consists of an inner and outer tube to direct oil flow uniformly (Figure 5). It is placed in the counting well of the scintillation detector where it is almost entirely surrounded by the scintillation crystal.

Figure 5. Counting Tube

As the wear debris in the oil contained in the small counting tube emit $\gamma$ radiation, by the action of photoelectric effect, energy of the $\gamma$ radiation is absorbed by the crystal and the scintillation, or "flashes of light" is produced in the crystal. These scintillations are detected by the photomultiplier tube which is optically coupled to the crystal, and then converted to electrical pulses. The pulse rate is proportional to the concentration of radio-active particles in the oil and therefore proportional to the accumulated ring wear.

These electrical pulses are then fed to the ratemeter which accumulates the number of total counts over a short period of time (usually 40 seconds) and indicates their average as a continuous reading of counts per minute. The output of the ratemeter is fed into a paper chart recorder. A continuous curve of counting rate against engine running time is plotted across the paper at a rate determined by the output and the selected scaling down ratio. Since the counting rate is directly proportional to the concentration of the radioactive iron particles in the lubricating oil, the slope of the counting rate is directly proportional to the concentration of the radioactive iron particles in the lubricating oil. The slope of the counting rate curve versus time plot on the chart recorder is directly proportional to the wear rate of the piston ring. With this system, the changes of wear rate can be observed immediately.

## PART VII

### WEAR RATE MEASUREMENT PROCEDURE

(1) Irradiation of the piston ring (4,5,6,15,20,21,22,23,26)

At the start of the program, the top compression ring, weighing 20 g., was sent to the Nuclear Reactor at McMaster University in Hamilton, Ontario for irradiation. The treatment of irradiation was by neutron bombardment for a period of 4 days. During this irradiating process, only a small portion of the iron atoms (about one atom in a billion) absorbing neutrons becomes the heavier radioactive iron isotope - $Fe^{59}$. This isotope acquires a level of activity equal to 0.5 mc per gram. The total activity for the 20 gram ring is about 10 mc (one millicurie equals $3.7 \times 10^7$ disintegrating atoms per second). The $Fe^{59}$ isotope emits $\beta$ and $\gamma$ rays spontaneously in the process of radioactive disintegration at a rate such that half of them will have disintegrated after 45.1 days. Therefore the half life is 45.1 days.

Table I shows the irradiation information supplied with the ring when delivered from the reactor.

Table II shows the radioactive constituents of the cast iron ring.

TABLE I. REACTOR IRRADIATION INFORMATION

Form MNR - 1
Revised June 1963

Reactor No. 64-V
Project No. AECB # 8-1837-66

Sample Name or Formula Cast Iron

Physical Form Piston Ring

Weight Approx. 20 gms.

Container Details Wrapped in Aluminum Foil, sealed in a tin can
pb sheet added for weighting can & to position sample

Reactor Position Desired Across Core Face (6C & 6D) Requested Time In 1200 hr. Mar. 22 1966

Irradiation Required 8 MWD Requested Time Out 1200 hr. Mar 26, 1966

Activity 10 mc Isotope $Fe^{59}$ Delivery Instructions

Estimated $\gamma$-Ray Shielding 1 in. of Pb

RESEARCHER University of Alberta DIRECTOR B.T. Stephanson

Approved for Irradiation J.B. McDougall Approval Date Mar. 22/66

IRRADIATION DATA

Sample Holder SH- with Short Spacer Other

| | | | |
|---|---|---|---|
| Position in Reactor | Across core face positions 6C & 6D | | |
| Time Installed | 1200 hr. Mar.22, 1966 | hr 196 | hr 196 |
| Irradiation Began | 1200 hr. Mar.22, 1966 | ~~hr 196~~ | ~~hr 196~~ |
| Irradiation Ended | 1200 hr. Mar.26, 1966 | ~~hr 196~~ | ~~hr 196~~ |
| Time Removed | 1200 hr. Mar.26, 1966 | ~~hr 196~~ | ~~hr 196~~ |
| M.W.H. Out | | | |
| M.W.H. In | | | |
| Integrated Power | 192.00 MWH | MWH | MWH |
| Power Level | 2.0 MWH | ~~MWH~~ | MWH |

DELIVERY

Shipping Container Identification U. of A. Shield Thickness 1 in. of P

Radiation through Container 15 mr hr Time and Date 0950 M.

Radiation Checked By

Sample Received By

TABLE II. RADIOACTIVE CONSTITUENTS OF IRRADIATED PISTON RING

| Element | % Weight in Ring (approximate) | Radioactive Isotope | Half-life | Radiation |
|---|---|---|---|---|
| Iron | 91 | $Fe^{55}$ | 2.94 yrs | k-capture |
| Iron | 91 | $Fe^{59}$ | 45.1 days | $\beta$ and $\gamma$ |
| Carbon | 3.75 | $C^{14}$ | 5570 yrs. | $\beta$ |
| Silicon | 2.65 | $Si^{31}$ | 2.65 hrs. | $\beta$ |
| Manganese | 0.60 | $Mn^{56}$ | 2.58 hrs. | $\beta$ and $\gamma$ |
| Phosphorus | 0.55 | $P^{32}$ | 14.3 days | $\beta$ |
| Sulfur | 0.06 | $S^{35}$ | 87.1 days | $\beta$ |
| Chromium | 0.30 | $Cr^{51}$ | 27.8 days | $\beta$ and $\gamma$ small amount |
| Molybdenum | 0.65 | $Mo^{99}$ | 67 hrs. | k-capture and small amount $\gamma$ |
| Copper | 0.50 | $Cu^{64}$ | 12.7 hrs. | k-capture $\beta$ and $\gamma$ |

After the ring had been removed from the nuclear reactor, it was held for two weeks before shipment to allow the radiation from the short lived manganese isotope to fall to a safe level. Then the ring was shipped in a lead box with a thickness about one inch on all sides. On receipt, the highest surface radiation level measured on the lead box with a freshly irradiated ring was about 50 mr/hr.

(2) Standard Solution (2,5,6,8,15,23,25,26,35)

The wear rate curve obtained from the recorder chart only shows the relative wear rates in counts per second which cannot tell the absolute engine wear rate. In order to convert the relative wear rate to absolute wear rate in milligrams of iron per hour, it is necessary to measure the activity in counts per second of the standard solution with the same counting instrument and geometry as used in counting the activity of the lubricating oil.

The standard solution was prepared as follows:

(a) A measured amount of iron sample weighing 0.3196 gm which has been irradiated was dissolved in the 1/10 sulfuric acid.

(b) After the iron piece was completely dissolved, it was diluted with water. The final concentration of the solution was 0.11056 mg/cc.

(c) From the solution, 4.96 c.c. was measured out, this is the volume of the counting tube, and put in a glass tube. The iron content in the glass tube was 0.548 mg.

Knowing the milligrams of irradiated iron in the standard solution, the measured activity of the standard solution was then converted to specific activity in counts per second per milligrams of iron. The actual wear rate in milligrams of iron per hour can be obtained by dividing the slope of the wear rate curve (rate of increase in radioactivity in the lubricating oil) by the specific activity and multiplying by the ratio of the volume of oil in the crankcase to the volume of oil in the counting tube. This calculation can be expressed by the following formula:

$$\text{Wear rate (mg Fe per hour)} = \frac{C}{A} \times \frac{O_c}{O_t}$$

C = Chart recorder curve slope in counts per second per hour

A = Specific activity in counts per sec. per mg. of iron

$O_c$ = Oil volume in the crankcase

$O_t$ = Oil volume in counting tube

(3) Test Operation

(a) After the new irradiated piston ring was installed in the engine, a break-in run was made. This period of operation was continued until the steady wear rate was reached.

(b) Following break-in run, the oil system was drained, flushed and refilled. Then the regular test run was started and the engine was operated under the desired test conditions.

(c) Before running the engine, the lubricating oil must be heated by turning on the oil heater, the cooling water must be circulated by turning on the cooling water valves.

(d) The engine was operated for 8 hours at each test condition. It was found that this was sufficient time to obtain accurate wear rates.

(e) In each test, the engine was run on one fuel for four hours. After this period of running, stable operation was reached and wear rate was steady as shown by curve on recorder chart. The engine was then switched to the other fuel for another four hours running and observation made on the wear rate.

(f) In each test, the engine should be operating at the best possible setting and adjustment for each fuel. During the test period, measurements of power output, fuel-air ratio and oil temperature were made every half hour.

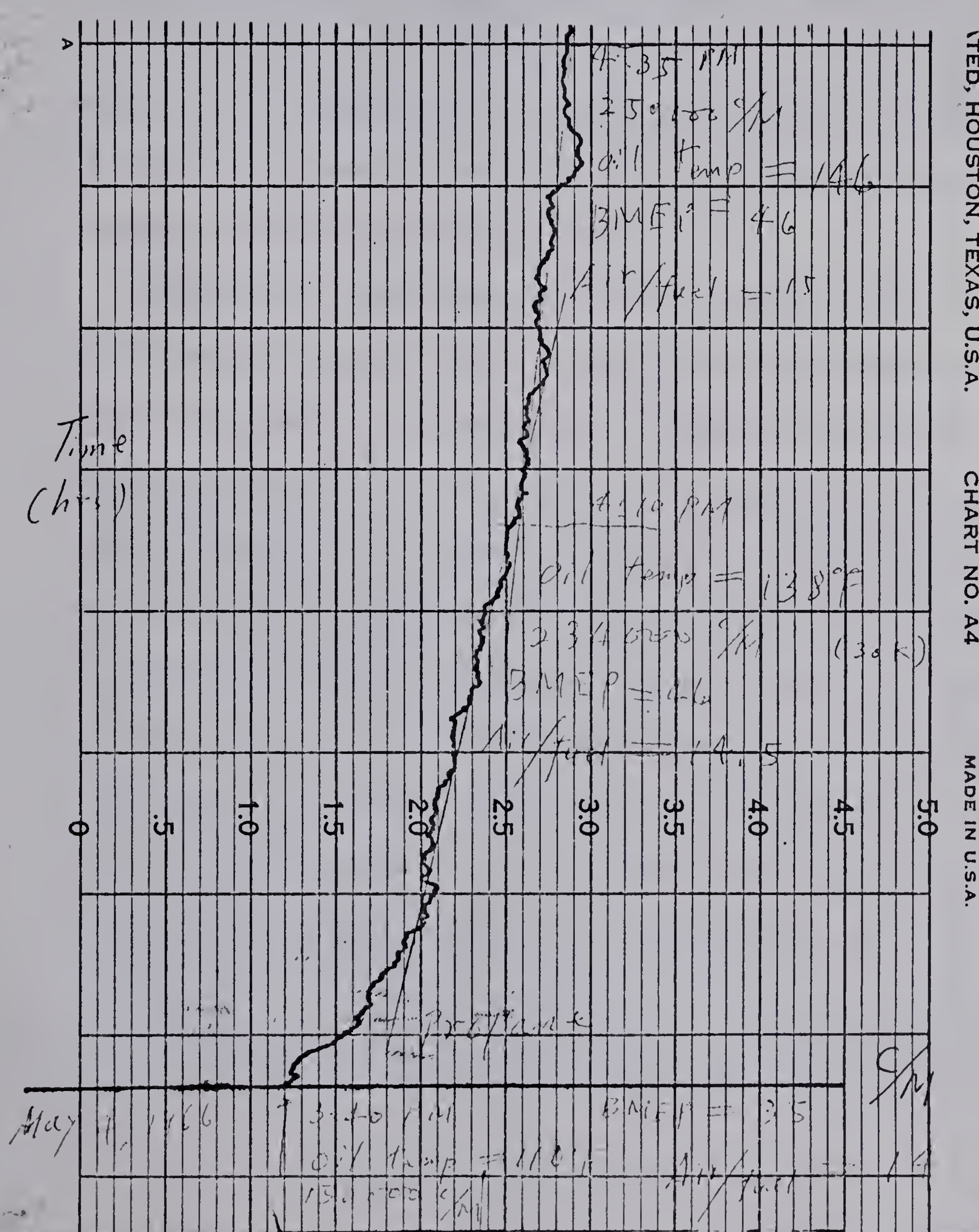
(g) At the conclusion of each test, the engine was stopped. The lubricating oil was changed to eliminate the possibility of dirty oil affecting wear rate of the next test.

(4) Sample curve obtained on recorder chart

Figure 6 illustrates the information recorded in a typical test run during warm up.

It will be noted that for about one half an hour after engine start that the wear rate was very high as indicated by the steep slope on the curve when the engine warmed up. The wear rate reduced to a stable rate as shown by the uniform slope or straight line.

Figure 6. Wear Rate at Start-up



## PART VIII

RADIATION SAFETY PRECAUTIONS (4,5,6,15,22,23,26,35)

After the piston ring was irradiated in the nuclear reactor, it emits $\beta$ and $\gamma$ rays spontaneously. Both of these rays are harmful to the human body. Beta rays are easily stopped by most materials. Although their penetrating power is low, they cause a hazard if ingested into the body or are absorbed through the skin. Gamma rays are very penetrating, several inches of lead are required to stop them effectively. Even though the radiation from the ring is not extremely dangerous, the problem of protecting operating personnel from the physical hazards of harmful radiation cannot be ignored.

According to some radiation safety documents, 100 milliroentgens per day is the maximum safe daily exposure from a health standpoint. The roentgen is a quantitative measure of the radiation exposure. One roentgen is the quantity of ionizing radiation which will dissipate 83 ergs in ionization per gram of body tissue. The accepted safe level of dosage is 0.1 roentgen, or 100 milliroentgen per 8 hour day or 0.3 roentgen per week. The dosage or levels of activity can be measured conveniently with a radiation survey meter (Figure 7) which is based on the ionizing effect of the radiation on a gas. This kind of monitoring instrument is excellent for both detection and dosage indication.

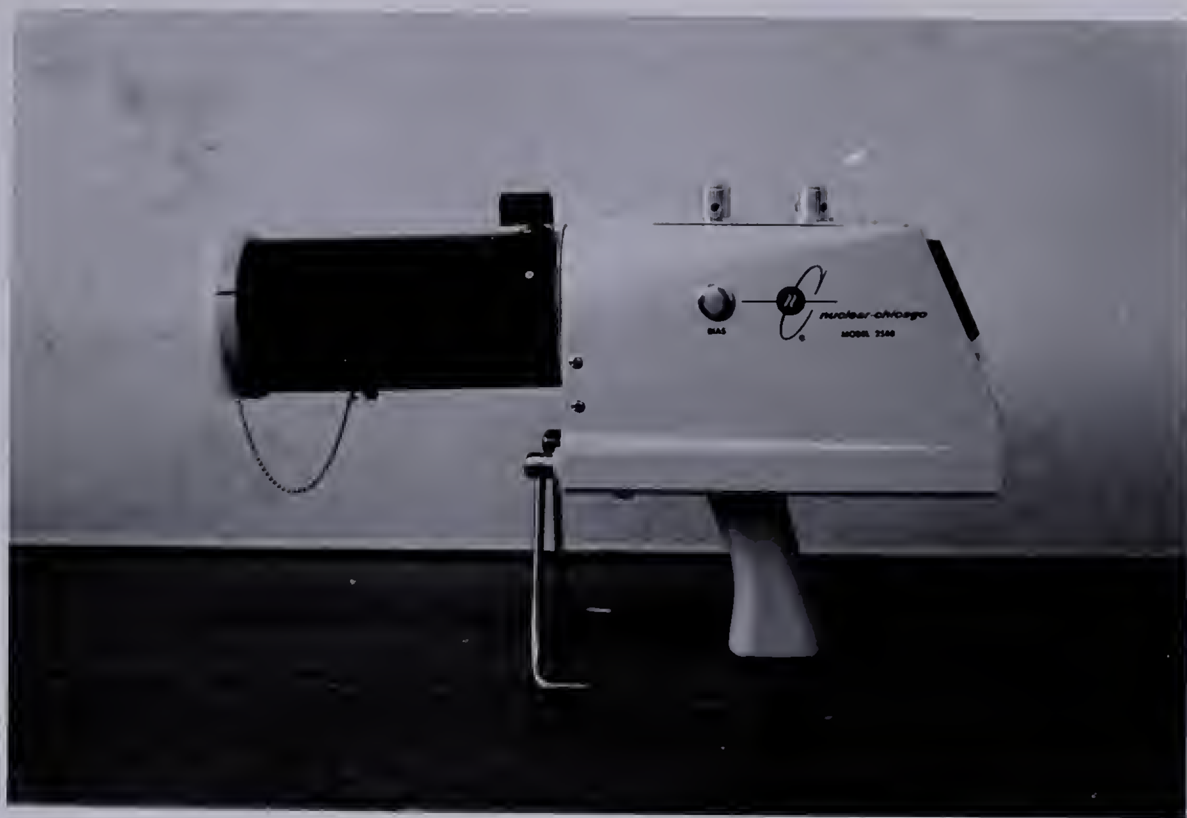


Figure 7. Radiation Survey Meter

Another safety monitoring device is the sensitive film badge (Figure 8). It is used for recording cumulative dosage and should be worn by project personnel.

Figure 8. Sensitive Film Badge

Greatest danger from radiation exposure occurs during installation of the irradiated piston ring in the test engine. At that moment, the ring is unshielded and the dosage is measured to be 500 mr/hr at a distance of 3 inches. To minimize the hazard during this operation, the following safety precautions are vitally important.

(1) Keep a sufficient distance from the radiation source — In general, the best protection from any type of radiation is distance. Since intensity decreases as the square of the distance. Of course, direct handling of the irradiated ring is extremely dangerous. The special tools for handling the ring such as the ring expanders and ring compressor (Figure 9) are constructed in such a way that the hands were at least two feet away from the radioactive material.

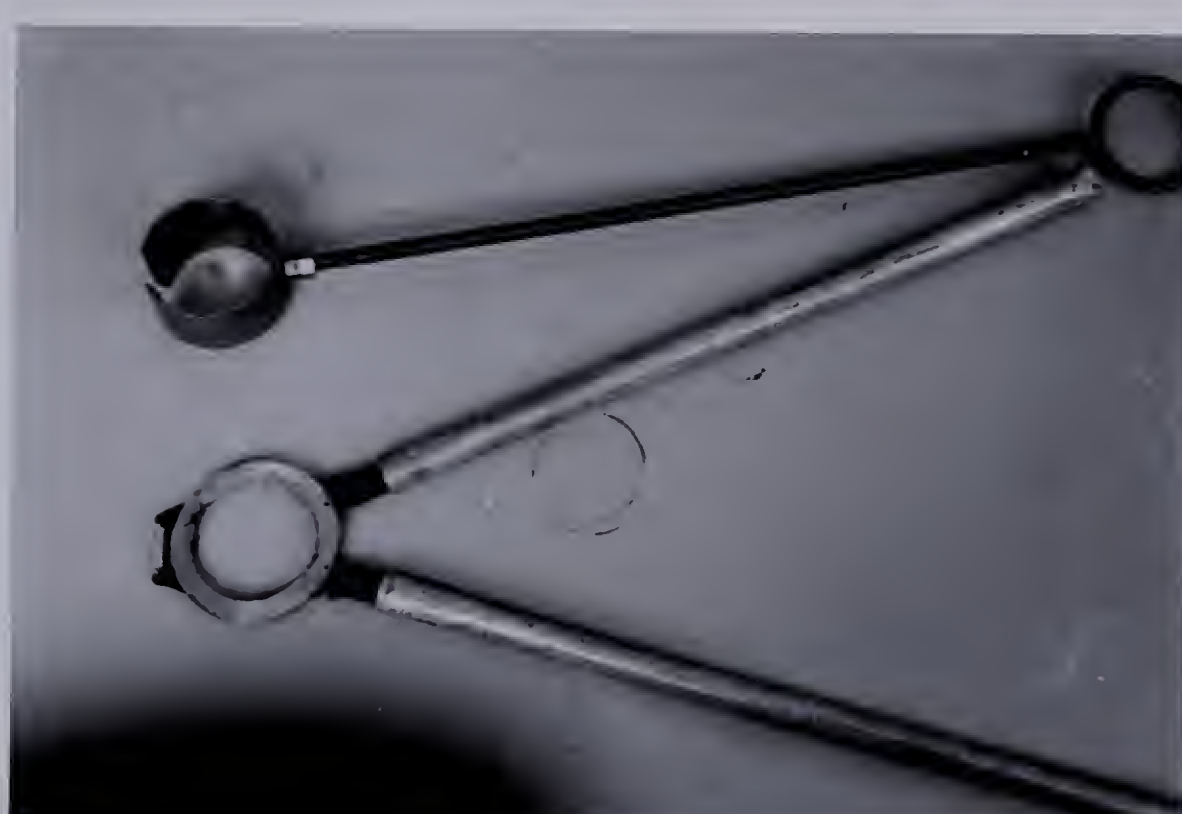


Figure 9. Ring Expander and Ring Compressor

(2) Keep the operating time as short as possible. The amount of dosage received is proportional to the exposure time. The installation was accomplished only 15 minutes from the time the lead box was opened to the time the ring was enclosed in the cylinder. The assembly time was limited to 15 minutes the first day, work was completed the second day in half an hour.

(3) Good shielding - Personnel should be shielded from the ring as much as possible to minimize the dosage when handling the ring or working around the engine. The best way for shielding is to wear lab-coat, eye shields or gloves when exposed to the unshielded ring to guard against both the $\beta$ and $\gamma$ radiation.

After assembly, although the radioactive ring is shielded by the water jacket and cylinder head, the radiation level around the engine is very low, (At an average radius of 8 inches around the engine cylinder and head the dosage measured by the radiation survey meter was 40 mr/hr) yet it is still dangerous to work in the vicinity of the engine for a considerable period of time. To avoid the radiation hazard, a suitable area was roped off about the engine at a sufficient distance to limit the radiation intensity to a safe level.

The lubricating oil in the test engine was changed at the end of each 8 hr. test run to remove accumulated radioactivity and

avoid possible carry-over effects from one run to the next. In draining the used oil, care should be taken to avoid contamination of the person by radioactive debris in the oil and rubber gloves should be used when handling oil samples.

Spilled oil drops around the engine or sampling containers should be wiped up immediately by absorbing paper towels. The used oil will be stored for a year to reduce the specific activity to a harmless level. Then it will be diluted at least 20:1 by inactive oil from other engines for proper disposal as waste.

# PART IX

# RESULTS

(1) Effect of lubricating oil temperature on engine wear. (7,31,33)

(A) Theory

In general, temperature changes have a considerable effect on the viscosity of oils. High temperatures reduce the viscosity of the oil. Low temperatures increase its viscosity. If the oil temperature is low and the oil too viscous, adequate flow to the cylinder especially during the first few minutes of running after the shutdown will not be established. The excessive wear of corrosion and scuffing on piston ring will take place owing to metal to-metal contact between the piston ring and the cylinder wall. On the other hand, if the oil temperature is too high, the oil viscosity will drop with the result that oil will drain off the cylinder to the crankcase, and extensive corrosion and scuffing will occur during the first few moments of operation before the oil supply is re-established.

Since no one has succeeded in developing a satisfactory lubricant that even approaches constant viscosity with temperature change, the best way to improve engine lubrication is to control the oil temperature variations by an oil temperature control system which can warm the oil when cold and cool the oil when hot.

In this test engine, the oil is warmed by the oil heater and cooled by the oil cooler. The normal crankcase oil temperature is 165 $\pm$ 5F. But in this experiment, it was necessary to set different oil temperatures for the wear rate measurement. Before starting the engine, crankcase oil was heated by turning on the oil heater. As the temperature, indicated by the thermometer, reached a certain temperature, the oil heater was switched to Low. If the temperature continued to rise, it was switched to the Off position. A further rise in temperature necessitated opening the oil-cooler valve which should be regulated to keep the oil temperature at the desired degree.

(B) Experimental Data

(i) The following table shows the different slopes measured from the record curves at different oil temperature.

TABLE III. DIFFERENT SLOPES OF THE CURVE AT DIFFERENT LUBRICATION TEMPERATURES

| Temperature (F) | Slopes of curves (c/m/hr) | |
|---|---|---|
| | Gasoline | Propane |
| 120 | $\tan 12^{\circ} = 0.2126$ | |
| 140 | $\tan 4^{\circ} = 0.0699$ | $\tan 14^{\circ} = 0.2493$ |
| 150 | $\tan 3.5^{\circ} = 0.0611$ | $\tan 1^{\circ} = 0.0174$ |
| 155 | $\tan 2.5^{\circ} = 0.0437$ | $\tan 3^{\circ} = 0.0524$ |
| 160 | $\tan 4^{\circ} = 0.0699$ | $\tan 3^{\circ} = 0.0524$ |
| 164 | $\tan 5^{\circ} = 0.0875$ | $\tan 5^{\circ} = 0.0875$ |

(ii) Calculation Data:

Background = 2000 c/m

Activity of standard solution = 6000 c/m

Net activity of standard solution = 4000 c/m

Iron content in standard solution = 0.548 mg.

Wear rate (mg/hr) $= \frac{C}{A} \times \frac{O_c}{O_t}$

C = Chart recorder curve slope (c/sec/hr)

A = Specific activity (c/sec/mg)

$$= \frac{4000 \text{ c/m}}{0.548 \text{ mg}} = \frac{4000/60 \text{ c/sec}}{0.548 \text{ mg}} = \frac{66.6 \text{ c/sec}}{0.548 \text{ mg}} = 121.53 \text{ c/sec/mg}$$

$O_c$ = Oil volume in crankcase

= 2.5 qt. = 2.5 x 946.3 = 2365.75 c.c.

$O_t$ = Oil volume in counting tube = 4.96 c.c.

(C) Calculations

(a) For gasoline

(1) At 120$^{o}$F

$$C = 0.2126 \text{ c/m/hr} = \frac{0.2126}{60} = 0.0035 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.0035}{121.53} \times \frac{2365.75}{4.96} = 0.0000287 \times 477 = 0.0137 \text{ mg/hr}$$

(2) At 140$^{o}$F

$$C = 0.0699 \text{ c/m/hr} = \frac{0.0699}{60} = 0.001165 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.001165}{121.53} \times \frac{2365.75}{4.96} = 0.0000095 \times 477 = 0.0045 \text{ mg/hr}$$

(3) At 150$^{o}$ F

$$C = 0.0611 \text{ c/m/hr} = \frac{0.0611}{60} = 0.00101 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.00101}{121.53} \times \frac{2365.75}{4.96} = 0.0000082 \times 477 = 0.004 \text{ mg/hr}$$

(4) At 155$^{o}$ F

$$C = 0.0437 \text{ c/m/hr} = \frac{0.0437}{60} = 0.000728 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.000728}{121.53} \times \frac{2365.75}{4.96} = 0.00000599 \times 477 = 0.0028 \text{mg/hr}$$

(5) At 160$^{o}$ F

$$C = 0.0699 \text{ c/m/hr} = \frac{0.0699}{60} = 0.001165 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.001165}{121.53} \times \frac{2365.75}{4.96} = 0.0000095 \times 477 = 0.0045 \text{ mg/hr}$$

(6) At 164$^{o}$ F

$$C = 0.0875 \text{ c/m/hr} = \frac{0.0875}{60} = 0.001458 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.001458}{121.53} \times \frac{2365.75}{4.96} = 0.0000119 \times 477 = 0.0057 \text{ mg/hr}$$

(b) For propane

(1) At 140°F

$$C = 0.2493 \ c/m/hr = \frac{0.2493}{60} = 0.004155 \ c/sec/hr$$

$$\text{Wear rate} = \frac{0.004155}{121.53} \times \frac{2365.75}{4.96} = 0.0000341 \times 477 = 0.0162 \ mg/hr$$

(2)At 150°F

$$C = 0.0174 \ c/m/hr = \frac{0.0174}{60} = 0.00029 \ c/sec/hr$$

$$\text{Wear rate} = \frac{0.00029}{121.53} \times \frac{2365.75}{4.96} = 0.00000238 \times 477 = 0.0011 \ mg/hr$$

(3) At 155 °F

$$C = 0.0524 \ c/m/hr = \frac{0.0524}{60} = 0.0008733 \ c/sec/hr$$

$$\text{Wear rate} = \frac{0.0008733}{121.53} \times \frac{2365.75}{4.96} = 0.00000718 \times 477 = 0.0034 \ mg/hr$$

(4) At 160°F

$$C = 0.0524 \ c/m/hr = \frac{0.0524}{60} = 0.0008733 \ c/sec/hr$$

$$\text{Wear rate} = \frac{0.0008733}{121.53} \times \frac{2365.75}{4.96} = 0.00000718 \times 477 = 0.0034 \ mg/hr$$

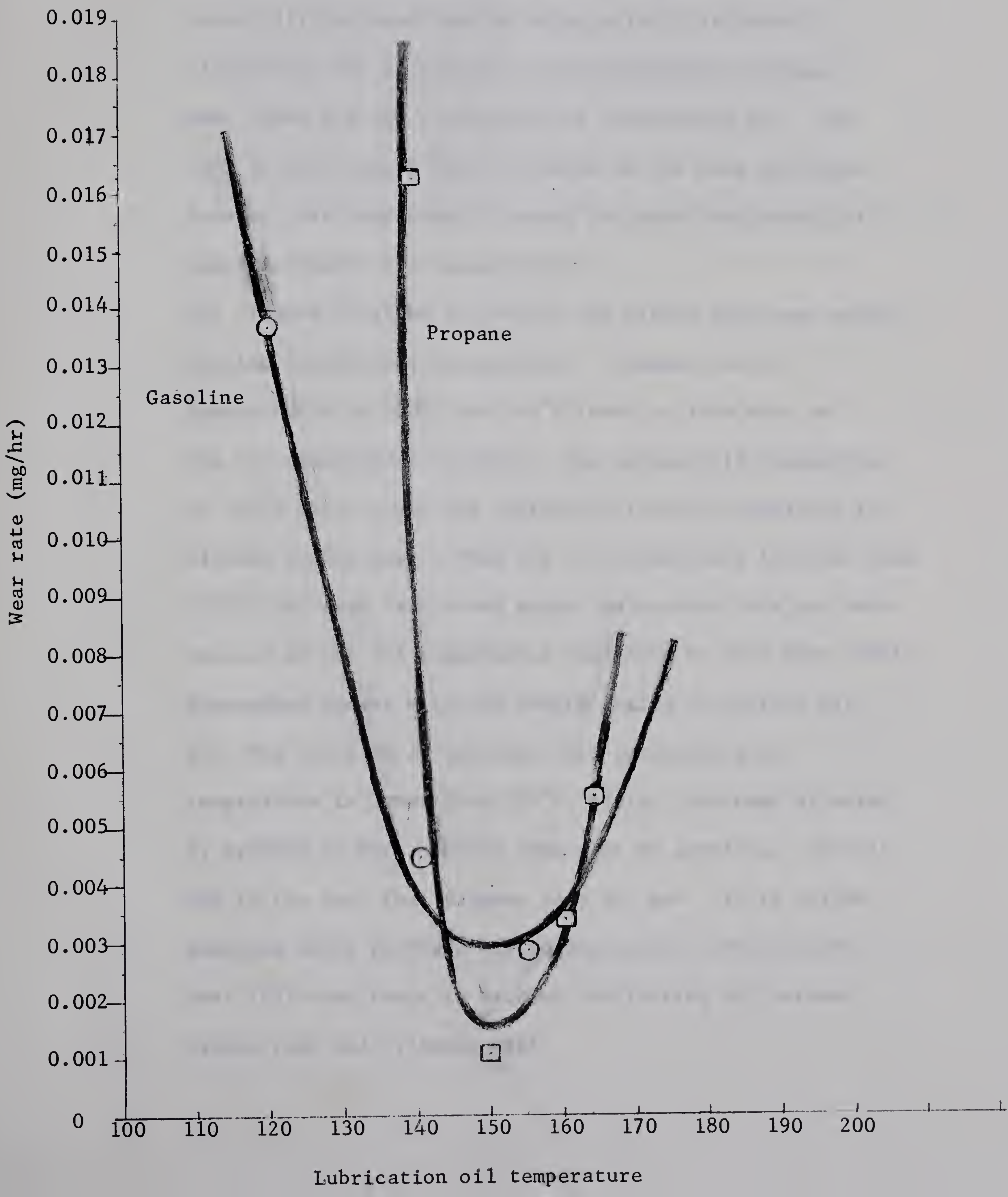
(5) At 164°F

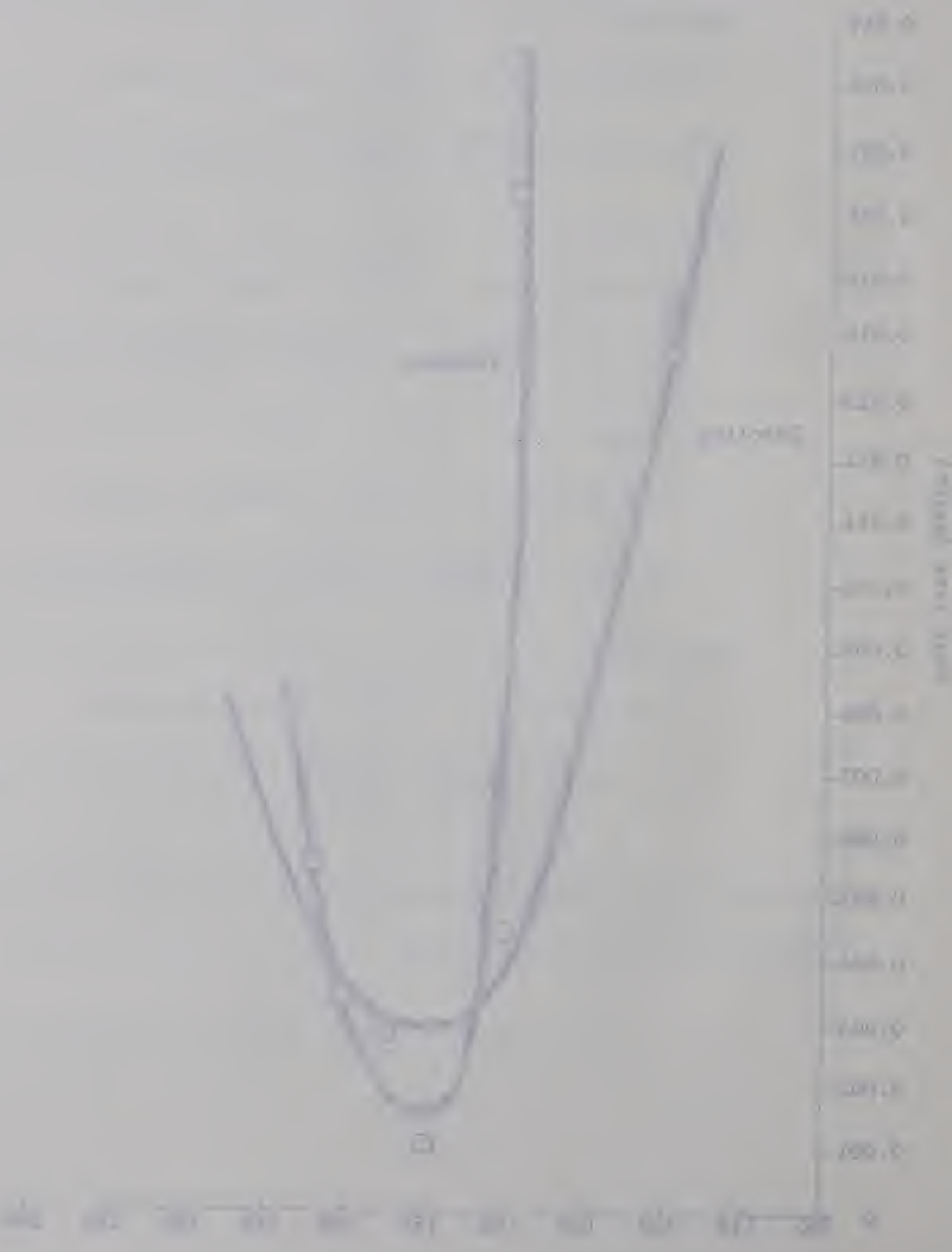
$$C = 0.0875 \ c/m/hr = \frac{0.0875}{60} = 0.001458 \ c/sec/hr$$

$$\text{Wear rate} = \frac{0.001458}{121.53} \times \frac{2365.75}{4.96} = 0.0000119 \times 477 = 0.0056 \ mg/hr$$

The relationship between piston ring wear rate and lubrication oil temperature is shown in Figure 10.

Figure 10. Plot of Piston Ring Wear Rate Versus Lubrication Oil Temperature





(D) Discussion

(1) This experiment was done according to the theory that the viscosity of lubricating oil is inversely proportional to its temperature and the engine wear is affected by the viscosity of lubricating oil. Previous tests (11) had been made by using oils of different viscosities for finding out the relationships between wear rates and the viscosities of lubricating oil. The test in this report which is based on the same principle, however, was undertaken by using the same lubricating oil under different oil temperatures.

(2) Figure 10 gives an idea of the piston ring wear under varying lubrication temperatures. Between the oil temperatures of 150°F and 165°F there is less wear as the oil temperature is lower. The optimum oil temperature is 150°F which gives the desirable viscosity resulting in minimum engine wear. When the oil temperature is lower than 150°F, the wear rate rises again and becomes more and more serious as the oil temperature continued to drop down. This phenomenon agrees with the theory stated in Section (A).

(3) The curve shows that when the lubricating oil temperature is lower than 150°F, piston ring wear affected by propane is more serious than that by gasoline. This is due to the fact that propane is a dry gas. It is unlike gasoline which provides liquid protection from friction wear (27) when there is lack of lubricating oil between piston ring and cylinder wall.

(4) When the lubricating oil temperature is higher than $150^{o}F$, the difference in wear rate between the effects of gasoline and propane is not significant.

(2) Effect of Air-fuel ratio on engine wear (11,26,32)

(A) Theory

A correct mixture of air and fuel was made up in the proportion of 15 parts by weight of air to 1 part by weight of fuel. In actual operation, however this ideal mixture was hard to maintain.

A fuel mixture containing less than the required amount of air is known as a rich mixture. A fuel mixture containing more than the required amount of air is known as a lean mixture. Leaner mixtures have the effect of accelerating wear rate. The fact is that at leaner mixtures, more corrosive products such as $CO_2$ are formed from combustion (11,32). This phenomenon was proved (11) by examining the exhaust gas condensate from which it was found that there were much higher acid numbers at the leaner settings than at rich settings. In this test, the air-fuel ratio was measured from the exhaust gas by an air-fuel ratio meter (Figure 11) which can take the readings of air-fuel ratio either using gasoline or propane as the engine fuel.

Figure 11. Air-fuel Ratio Meter

The following result shows that when the air-fuel ratio was made leaner, the wear rate increased considerably.

(B) Experimental Data

(i) The following table shows the different slopes measured from the record curves at different air-fuel ratios under constant oil temperature.

TABLE IV. DIFFERENT SLOPES OF THE CURVE AT DIFFERENT AIR-FUEL RATIOS

| Fuels | Air-fuel ratios | Slopes of curves (c/m/hr) |
|---|---|---|
| Gasoline | 12.6 | $\tan 3^{o} = 0.0524$ |
| | 12.7 | $\tan 4^{o} = 0.0699$ |
| | 13.4 | $\tan 5^{o} = 0.0875$ |
| | 13.5 | $\tan 5^{o} = 0.0875$ |
| Propane | 14.5 | $\tan 1^{o} = 0.0174$ |
| | 14.6 | $\tan 3^{o} = 0.0524$ |
| | 14.7 | $\tan 3^{o} = 0.524$ |
| | 15 | $\tan 6^{o} = 0.1051$ |

(ii) Calculation Data:

Background = 1900 c/m

Activity of standard solution = 4900 c/m

Net activity of standard solution = 3000 c/m

Iron content in standard solution = 0.548 mg.

$$\text{Wear rate (mg/hr)} = \frac{C}{A} \times \frac{O_c}{O_t}$$

C = Chart recorder curve slope (c/sec/hr)

A = Specific activity (c/sec/mg)

$$= \frac{3000 \text{ c/m}}{0.548 \text{ mg}} = \frac{3000/60 \text{ c/sec}}{0.548 \text{ mg}} = \frac{50 \text{ c/sec}}{0.548 \text{ mg}} = 91.24 \text{ c/sec/mg}$$

$O_c$ = Oil volume in crankcase = 2.5 qt. = 2.5 $\times$ 946.3 = 2365.75 c.c.

$O_t$ = Oil volume in counting tube = 4.96 c.c.

(C) Calculations

(a) For gasoline

(1) air/fuel = 12.6

$$C = 0.0524 \text{ c/m/hr} = \frac{0.0524}{60} = 0.0008733 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.0008733}{91.24} \times \frac{2365.75}{4.96} = 0.00000957 \times 477$$

$$= 0.0046 \text{ mg/hr}$$

(2) air/fuel = 12.7

$$C = 0.0699 \text{ c/m/hr} = \frac{0.0699}{60} = 0.001165 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.001165}{91.24} \times \frac{2365.75}{4.96} = 0.00001276 \times 477$$

$$= 0.006 \text{ mg/hr}$$

(3) air/fuel = 13.5

$$C = 0.0875 \text{ c/m/hr} = \frac{0.0875}{60} = 0.001458 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.001458}{91.24} \times \frac{2365.75}{4.96} = 0.0000159 \times 477$$

$$= 0.0076 \text{ mg/hr}$$

(4) air/fuel = 13.5

$$C = 0.0875 \text{ c/m/hr} = \frac{0.0875}{60} = 0.001458 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.001458}{91.24} \times \frac{2365.75}{4.96} = 0.0000159 \times 477$$

$$= 0.0076 \text{ mg/hr}$$

(b) For propane

(1) air/fuel = 14.5

$$C = 0.0174 \text{ c/m/hr} = \frac{0.0174}{60} = 0.00029 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.00029}{91.24} \times \frac{2365.75}{4.96} = 0.00000318 \times 477$$

$$= 0.0015 \text{ mg/hr}$$

(2) air/fuel = 14.6

$$C = 0.0524 \text{ c/m/hr} = \frac{0.0524}{60} = 0.0008734 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.0008734}{91.24} \times \frac{2365.75}{4.96} = 0.00000957 \times 477$$

$$= 0.0046 \text{ mg/hr}$$

(3) air/fuel = 14.7

$$C = 0.0524 \text{ c/m/hr} = \frac{0.0524}{60} = 0.0008734 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.0008734}{91.24} \times \frac{2365.75}{4.96} = 0.00000957 \times 477$$

$$= 0.0046 \text{ mg/hr}$$

(4) air/fuel = 15

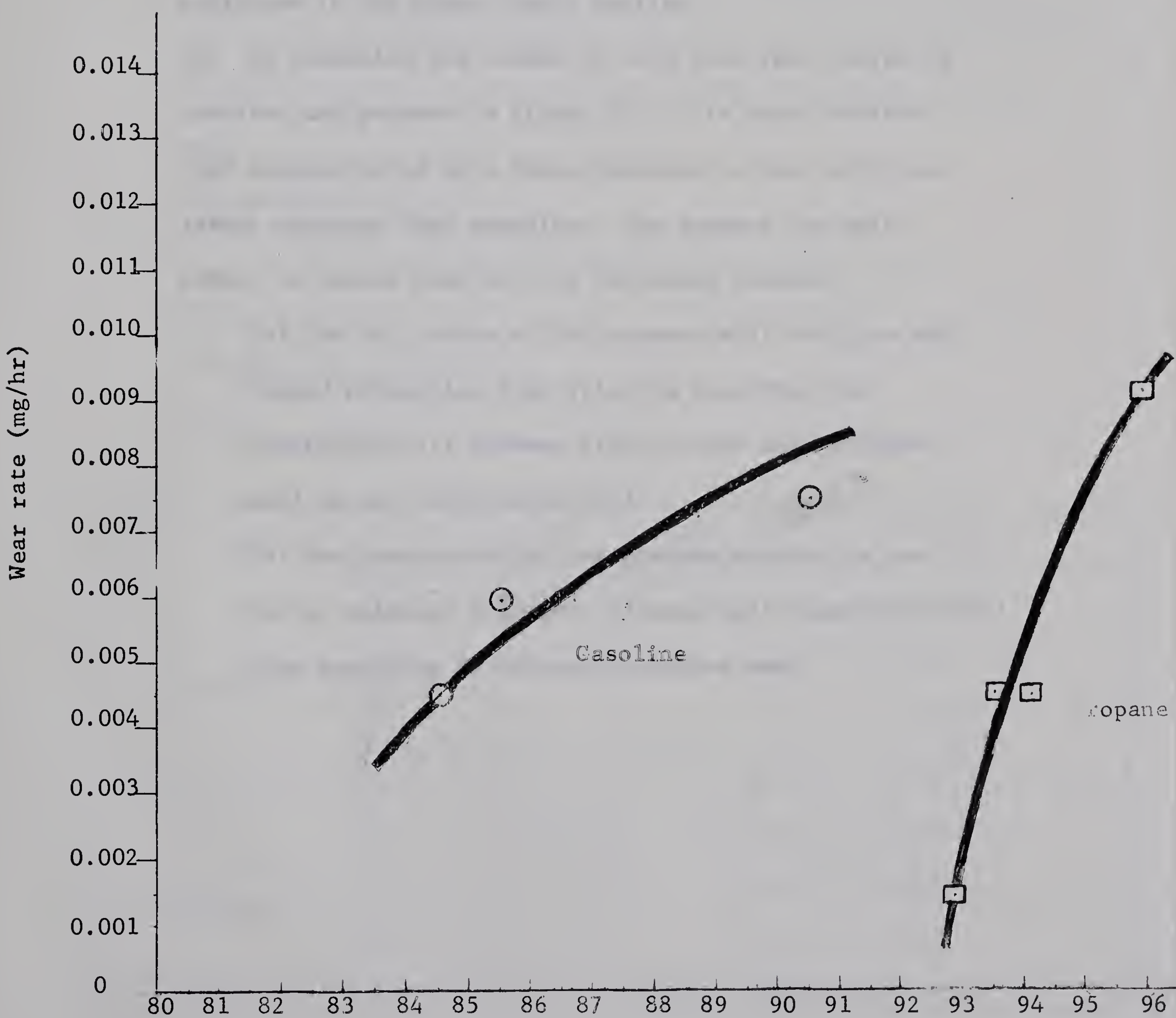
$$C = 0.1051 \text{ c/m/hr} = \frac{0.1051}{60} = 0.0017517 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.0017517}{91.24} \times \frac{2365.75}{4.96} = 0.0000192 \times 477$$

$$= 0.0091 \text{ mg/hr}$$

The wear rate determined at various air-fuel ratios is plotted in Figure 12.

Figure 12. Plot of Piston Ring Wear Rate Versus Air-Fuel Ratio




Air-fuel ratio expressed in percent of chemically correct mixture.

(D) Discussion

(1) Figure 12 shows that when the air-fuel ratio was made leaner, both the wear rates affected by gasoline and propane increased considerably. This finding agrees substantially with the reports (11,26,32) which showed that leaner mixtures accelerate piston ring wear to a considerable degree, the reason why leaner mixtures have the effect to accelerate wear rate has been explained in the above theory section.

(2) By observing the slopes of both wear rate curves of gasoline and propane in Figure 12, it is quite obvious that propane gives more sharp increase in wear with the leaner mixtures than gasoline. The propane has more effect on engine wear for the following reasons:

(a) The dry nature of the propane will not give any liquid protection from friction wear when the lubrication oil between piston rings and cylinder wall is not sufficient. (27)

(b) The temperature of the propane mixture is too low to maintain a proper cylinder wall temperature (32) thus resulting in extreme corrosive wear.

(3) Effect of engine load, brake mean effective pressure(bmep), on engine wear (3,20 25)

(A) Theory

The most important operating variable affecting piston ring wear is engine load according to Pinotti, et al. (20) In studying the effect of engine load on wear, it was found that both the wear rates arrected by gasloine and propane increased markedly as load was reduced. This phenomenon is connected with lacquering in the cylinder due to incomplete combustion of the fuel at lighter load (3). This lacquer containing very corrosive organic acids is the main product resulting in higher wear.

(B) Experimental Data

(i) The following table shows the different slopes measured from the record curves at different engine load under constant oil temperature.

TABLE V. DIFFERENT SLOPES OF THE CURVE AT DIFFERENT ENGINE LOADS

| Fuel | bmep | Slopes of curves (c/m/hr) |
|---|---|---|
| Gasoline | 54 | $\tan 5^{\circ} = 0.0875$ |
| | 56 | $\tan 4^{\circ} = 0.0699$ |
| | 57 | $\tan 3.5^{\circ} = 0.0611$ |
| | 58 | $\tan 3^{\circ} = 0.0524$ |
| Propane | 46 | $\tan 7^{\circ} = 0.1228$ |
| | 50 | $\tan 5^{\circ} = 0.0875$ |
| | 52 | $\tan 4^{\circ} = 0.0699$ |
| | 55 | $\tan 3.5^{\circ} = 0.0611$ |

(ii) Calculation Data:

Background = 3500 c/m

Activity of standard solution = 6500 c/m

Net Activity of standard solution = 3000 c/m

Iron content of standard solution = 0.548 mg

Wear rate = (mg/hr) $= \frac{C}{A} \times \frac{O_c}{O_t}$

C = Chart recorder curve slope (c/sec/hr)

A = specific activity (c/sec/mg) $= \frac{3000 \text{ c/m}}{0.548 \text{ mg}} = \frac{3000 \text{ c/sec/mg}}{60 \times 0.548}$

$= 91.24$ c/sec/mg

$O_c$ = Oil volume in crankcase

= 2.5 qt. = 2.5 x 946.3 = 2365.75 c.c.

$O_t$ = Oil volume in counting tube = 4.96 c.c.

(C) Calculations

(a) For gasoline

(1) bmep = 54

$C = 0.0875 \text{ c/m/hr} = \frac{0.0875}{60} = 0.001458 \text{ c/sec/hr}$

$\text{Wear rate} = \frac{0.001458}{91.24} \times \frac{2365.75}{4.96} = 0.0000159 \times 477$

$= 0.0076 \text{mg/hr}$

(2) bmep = 56

$C = 0.0699 \text{ c/m/hr} = \frac{0.0699}{60} = 0.001165 \text{ c/sec/hr}$

$\text{Wear rate} = \frac{0.001165}{91.24} \times \frac{2365.75}{4.96} = 0.00001277 \times 477$

$= 0.0061 \text{mg/hr}$

(3) bmep = 57

$C = 0.0611 \text{ c/m/hr} = \frac{0.0611}{60} = 0.0010184 \text{ c/sec/hr}$

$\text{Wear rate} = \frac{0.0010184}{91.24} \times \frac{2365.75}{4.96} = 0.00001116 \times 477$

$= 0.0053 \text{mg/hr}$

(4) bmep = 58

$$C = 0.0524 \text{ c/m/hr} = \frac{0.0524}{60} = 0.000873 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.000873}{91.24} \times \frac{2365.75}{4.96} = 0.00000957 \times 477$$

$$= 0.0046 \text{mg/hr}$$

(b) For propane

(1) bmep = 46

$$C = 0.1228 \text{ c/m/hr} = \frac{0.1228}{60} = 0.002046 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.002046}{91.24} \times \frac{2365.75}{4.96} = 0.0000224 \times 477$$

$$= 0.0107 \text{mg/hr}$$

(2) bmep = 50

$$C = 0.0875 \text{ c/m/hr} = \frac{0.0875}{60} = 0.001458 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.001458}{91.24} \times \frac{2365.75}{4.96} = 0.0000159 \times 477$$

$$= 0.0076 \text{mg/hr}$$

(3) bmep = 52

$$C = 0.0699 \text{ c/m/hr} = \frac{0.0699}{60} = 0.001165 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.001165}{91.24} \times \frac{2365.75}{4.96} = 0.00001276 \times 477$$

$$= 0.0061 \text{mg/hr}$$

(4) bmep = 55

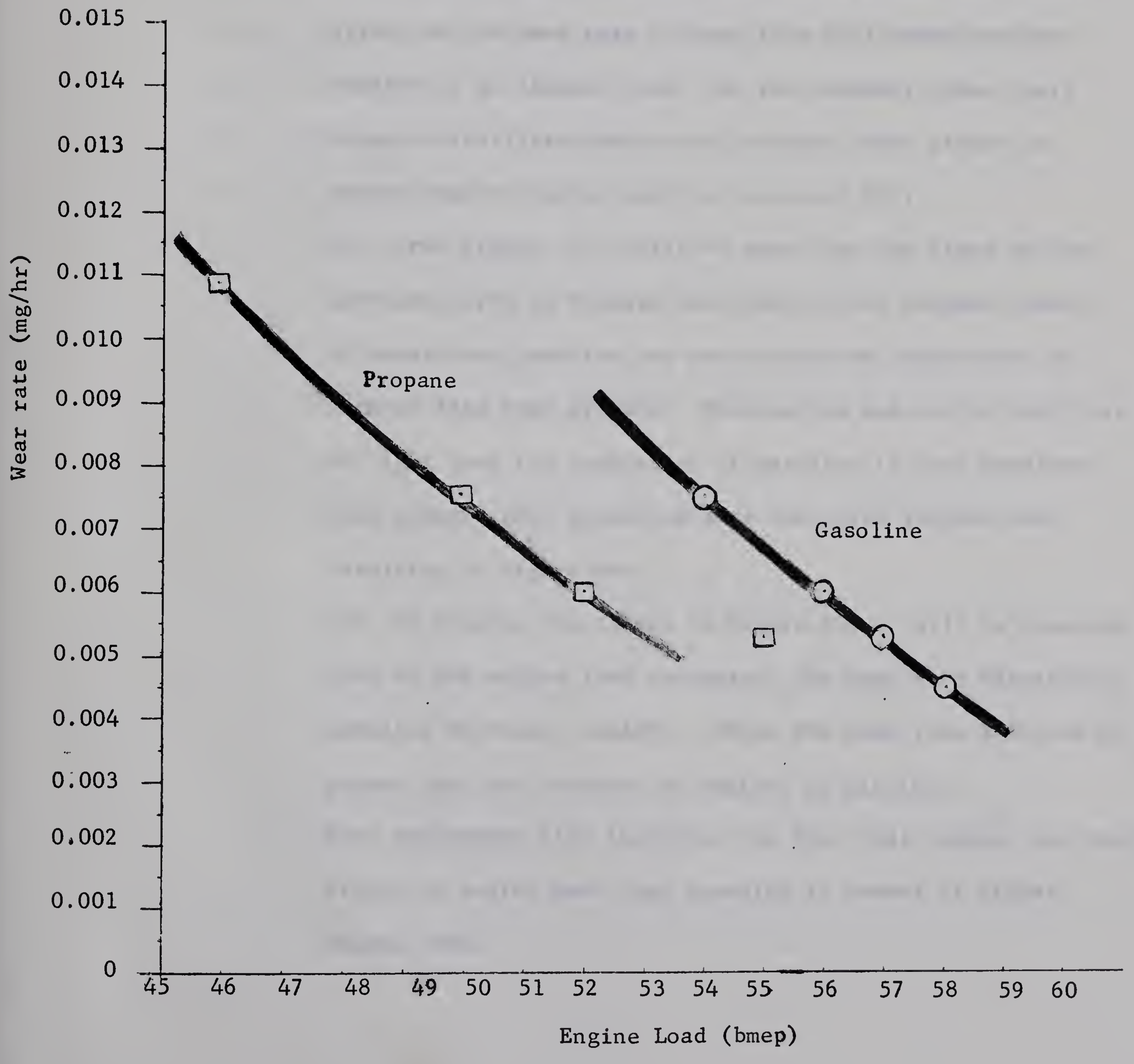
$$C = 0.0611 \text{ c/m/hr} = \frac{0.0611}{60} = 0.001018 \text{ c/sec/hr}$$

$$\text{Wear rate} = \frac{0.001018}{91.24} \times \frac{2365.75}{4.96} = 0.00001116 \times 477$$

$$= 0.0053 \text{mg/hr}$$

The ring wear rate is plotted against bmep for gasoline and propane as shown in Figure 13.

Figure 13. Plot of Piston Ring Wear Rate Versus Engine Load



(D) Discussion

(1) Figure 13 shows that the wear rates affected by gasoline and propane decreased markedly as engine load (bmep) was increased. This result agrees with one report (25). The reason why engine wear rate decreased with increasing of the engine load has been explained in the above theory section. But this theory is not true for all kinds of fuels. For example, engine load has an almost negligible effect on the wear rate of some fule (25) which can burn completely at lighter load. On the contrary, some fuels such as distillate fuels even increase their effect on engine wear as engine load is increased (20).

(2) From Figure 13 it will be seen that the slope of the gasoline curve is steeper than that of the propane curve. It means that gasoline has more effect on engine wear at lighter load than propane. This may be due to the fact that at light load the combustion of gasoline is less complete than propane thus producing more corrosive lacquer and resulting in higher wear.

(3) By tracing the curves in Figure 13, it will be observed that as the engine load increases, the wear rate affected by gasoline decreases rapidly. While the wear rate affected by propane may not decrease as rapidly as gasoline.
This phenomenon also indicates the fact that propane has more effect on engine wear than gasoline at normal or higher engine load.

# PART X

## CONCLUSION

(1) When the lubricating oil temperature was at $150^{\circ}$ F, both the wear rates for gasoline and propane were a minimum.

(2) When the lubricating oil temperature decreased below $150^{\circ}$F, the wear rate for both gasoline and propane increased rapidly. This effect was more pronounced at the lower temperatures for propane.

(3) When the air-fuel ratio was made leaner, the wear rate increased considerably. The wear rate affected by propane increased more rapidly than that of gasoline as air-fuel ratio increased.

(4) Decreasing engine load produced a marked increase in piston ring wear for both gasoline and propane.

(5) The method of continuous measurement of the activity of the radioactive wear debris in the lubricating oil is an excellent method for determining the engine wear rate. Since a continuous wear curve permits the immediate observation of changes that occur in a short time interval.

# PART XI

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# PART XII

## APPENDIX

(A) Propane as an engine fuel

(1) Physical properties (1,9,14,18,30,34)

The physical properties of propane are shown in Table VI.

TABLE VI. PHYSICAL PROPERTIES OF PROPANE

| | |
|---|---|
| Formula | $C_3H_8$ |
| Molecular weight | 44.094 |
| Boiling point of liquid at atmospheric pressure | -44$^{o}$F |
| Weight of liquid at 60$^{o}$F in lbs. per gallon | 4.23 |
| Specific gravity of liquid at 60$^{o}$F | 0.509 |
| Specific gravity of gas compared to air | 1.52 |
| BTU per gal of liquid at 60$^{o}$F | 91700 |
| BTU per lb of gas | 21690 |
| BTU per cu ft of gas at 60$^{o}$F, 14.7 psia | 2521 |
| cu ft of gas per lb of liquid at 60$^{o}$F, 14.7 psia | 8.59 |
| cu ft of gas per gal of liquid | 36.5 |
| vapor pressure, psi. gage, at 60$^{o}$F | 92 |
| vapor pressure, psi,gage, at 100$^{o}$F | 172 |
| critical compression ratio | 12:1 |
| self-ign. temp. $^{o}$F | 995 |
| Octane rating | 100 |
| Latent heat of vaporization, BTU per gal. | 788 |
| Optimum air-fuel ratio by weight | 15.6:1 |
| Freezing point $^{o}$F, Liq. | -305.9 |

(2) Principle of propane carburetion (1,9,14,18,24)

The conventional propane carburetion system used today is the type of standard conversion in which liquid is withdrawn from the fuel tank. Basically it consists of a special fuel container, filter, high-pressure regulator, vaporizer, low-pressure regulator, and a special LP gas carburetor. Figure 14 shows a flow diagram of a complete propane fuel-supply and carburetion system.

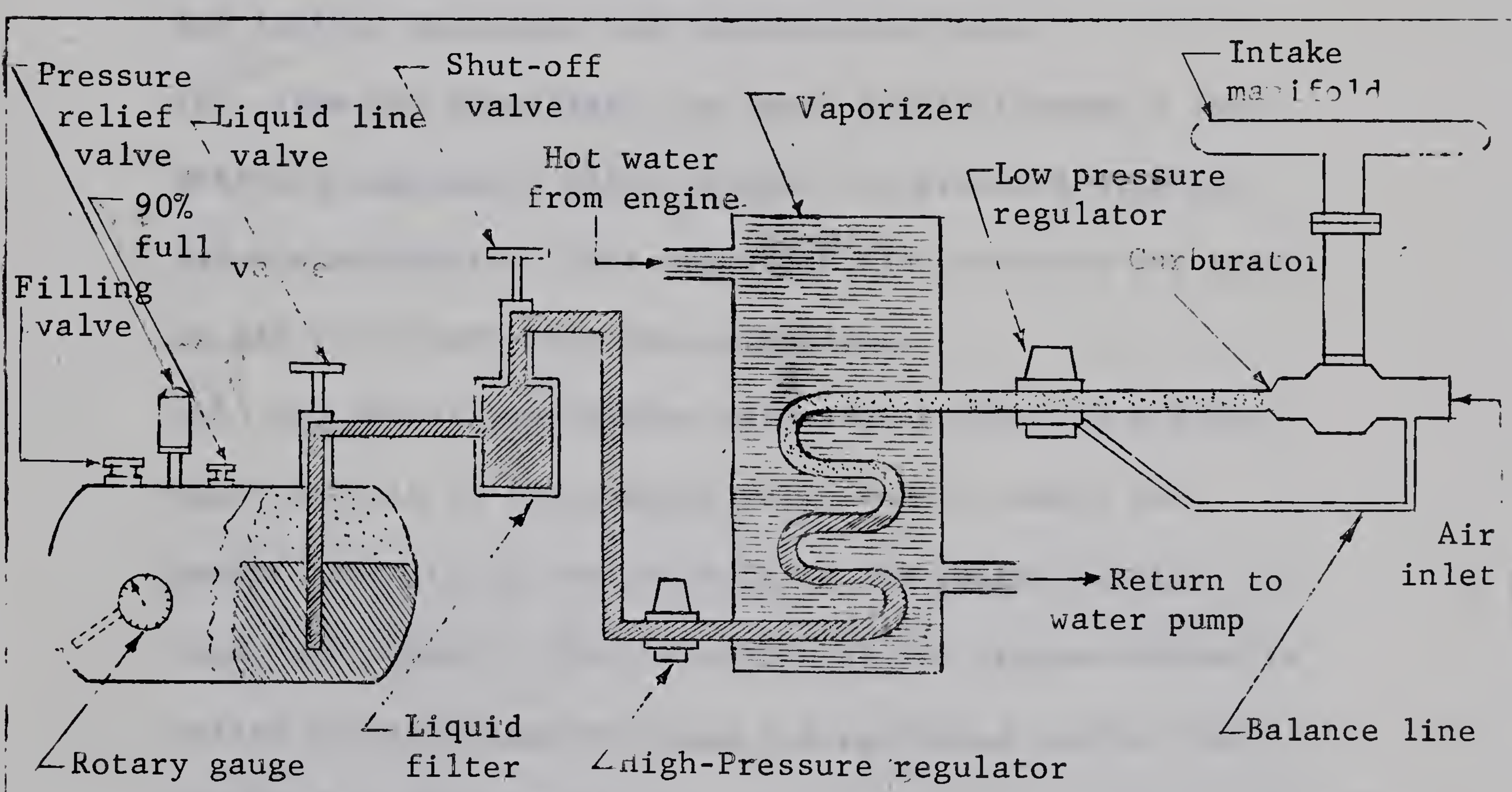


Figure 14. Propane Fuel-Supply and Carburetion System

The function of the propane carburetion system is stated as follows.

(a) The vapor pressure over the fuel forces the liquid fuel through a tube connected to an outlet at the top of the fuel tank.

(b) The liquid fuel passes through a filter to a high-pressure regulator that reduces the pressure of the fuel to about 8 lb. per sq. in., and partial expansion and vaporization begins.

(c) The fuel then enters the vaporizer, this is surrounded by heated water from the engine cooling system, and further expansion and vaporization occur.

(d) From the vaporizer, the vapor passes through a low-pressure regulator, which reduces its pressure slightly below atmospheric. This regulator also controls the amount of gas that flows into the carburetor.

(e) The special carburetor serves as a mixer to mix the vapor and air in the correct ratio and to supply the proper quantity of this mixture to the engine at all loads and speeds. The carburetor of the propane engine is bolted to the intake manifold and is sealed against the entrance of dust and dirt.

(3) Advantages of propane used as engine fuel (9,14,31,34)

(a) As the fuel is stored under pressure, there is no need for a fuel pump.

(b) Propane has better anti-detornating properties, which tend to give smooth, powerful and efficient operation without the ill effects on the engine.

(c) Propane has a high octane rating of about 100. Hence it can be used in high compression engines (The compression ratios are 8:1 - 10:1). These high ratios permit greater brake-horsepower production from engines of the same size because of greater thermal efficiency.

(d) Since it is a dry gas it mixes readily with air and burns cleanly and completely without leaving carbon residue, the engine wear is thus reduced.

(e) Being in a vapor form, propane will not go down to the crankcase and dilute the lubrication oil.

(f) No exhaust odors.

(g) Good fuel economy.

(4) Disadvantages of propane used as engine fuel (14,31,34)

(a) Propane gives less horsepower-hour output per gallon than gasoline or diesel fuel.

(b) The high pressure existing in the storage tanks and equipment increases the possibility of leakage and consequent explosion.

(c) Because of the bulky, pressurized tanks, storage and re-fuelling is cumbersome.

(d) Propane engine is hard to start in cold weather, because vapor pressure is difficult to build up.

(e) Propane is somewhat harder to produce in large quantities, therefore it is not practical as a general tractor or automotive fuel.

(B) Gasoline and propane fuel-consumption measurements

In order to find out which fuel gasoline and propane gives less consumption when running the engine,a series of fuel consumption rate measurements for gasoline and propane were made respectively.

Owing to the fact that both fuels give different consumption rates under different compression ratios, it is necessary to compare the consumption rate between these two fuels under a certain compression ratio. The following measurements were undertaken when the compression ration was 8:1.

(1) Measurement of gasoline consumption

In determining the consumption rate of gasoline, a fuel weighing system was employed. This system consists of beam scales for holding balancing weights and a beaker of fuel. (Figure 15)

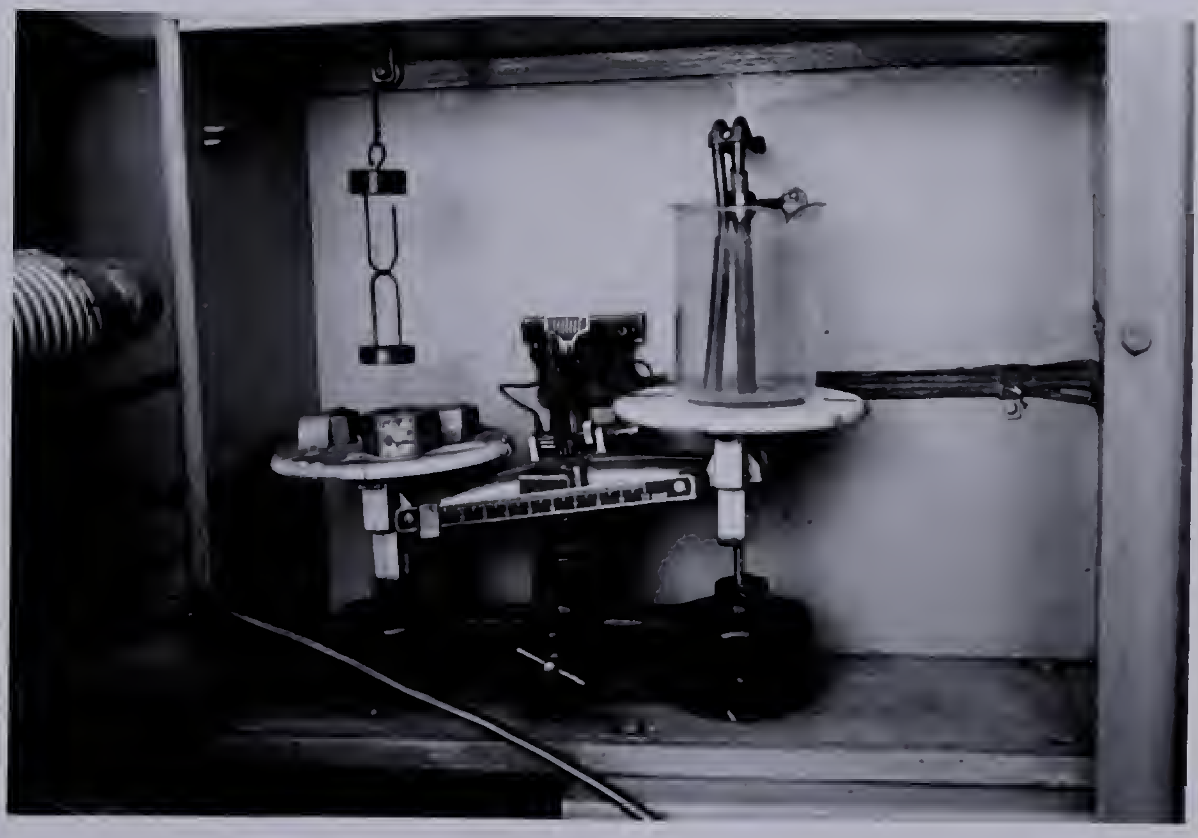

Figure 15. Equipment of Gasoline Consumption Rate Measurement.

It is equipped with automatic electrical starting, holding, and stopping circuits which start and stop an elapsed time electric clock.

By this weighing device, the time required for the engine to consume definite weight of fuel can be measured. The electrical system and the flow of fuel to the engine were controlled by manipulating two valves, tow preset switches and a scale-weight lever. The measuring data is listed in the following table.

TABLE VII. GASOLINE CONSUMPTION RATE MEASUREMENT

| Compression Ratio | bmep ($lbs/in^2$) | Gasoline Weight (lbs) |
|---|---|---|
| 8:1 | 58 | 0.25 |

| Time (min.) | Consumption rate = $\frac{\text{gasoline weight}}{\text{time}}$ (lbs/min) |
|---|---|
| 2.42 | 0.103 |
| 2.41 | 0.103 |
| 2.39 | 0.104 |
| 2.41 | 0.103 |
| Average consumption rate (lbs/hr) | 6.195 |

To convert the unit of lbs/hr to lbs/hp-hr, the average consumption rate must be divided by the value of bhp.

$$\text{bhp} = \frac{\text{PLAN}}{33000 \times 2}$$

P = bmep = 58 lb in$^2$

L = length of piston stroke = $\frac{4.5}{12}$ = 0.375 ft.

A = area of cylinder = (bore)$^2$ x 0.7854

= (3.25)$^2$ x 0.7854 = 8.3 in$^2$

N = engine speed = 1800 rpm

$$\text{bhp} = \frac{58 \times 0.375 \times 8.3 \times 1800}{33000 \times 2} = 4.92$$

$\therefore$ gasoline consuption rate = $\frac{6.195}{4.92}$ = 1.25 lbs/hp-hr

(2) Measurement of propane consumption

Propane consumption rate was measured with a weighing scale on which the propane tank was located (Figure 16).

Figure 16. Equipment of Propane Consumption Rate Measurement

At first, the propane in the tank was weighed. When the engine was running, the suspended scale beam gradually lost its balance situation and kept dropping until it dropped completely. The length of this dropping period was recorded by the stop watch. Then the propane was weighed again. By subtracting the final weight from the original weight and dividing by the time elapsed, the consumption rate of propane can be obtained. Repeat the cycle for each measurement of propane consumption as many times as possible, the average consumption rate will be very accurate. The measuring data is listed in the following table.

TABLE VIII. PROPANE CONSUMPTION RATE MEASUREMENT

| Compression Ratio | bmep ($lbs/in^2$) | bhp |
|---|---|---|
| 8:1 | 55 | 4.67 |

| ORIGINAL WEIGHT | TIME ELAPSED (mins.) | FINAL WEIGHT | CONSUMPTION RATE = $\frac{\text{original weight-final weight}}{\text{time elapsed}}$ (lbs/min.) |
|---|---|---|---|
| 34 lb 10 oz | 6.5 | 34 lb 5 oz | 0.048 |
| 34 lb 5 oz. | 6.0 | 34 lb 1 oz | 0.0416 |
| 34 lb 1 oz. | 6.2 | 33 lb 12 oz | 0.0504 |
| 33 lb 12 oz | 6.1 | 33 lb 8 oz | 0.0409 |
| 33 lb 8 oz | 61.5 | 33 lb 4 oz | 0.0406 |
| 33 lb 4 oz | 6.0 | 33 lb 0 oz | 0.0416 |
| 33 lb 0 oz | 6.0 | 32 lb 12 oz | 0.0416 |
| 32 lb 12 oz | 6.0 | 32 lb 9 oz | 0.0311 |
| 32 lb 9 oz | 6.3 | 32 lb 5 oz | 0.0396 |
| 32 lb 5 oz | 6.35 | 32 lb 1 oz | 0.0393 |
| Average consumption rate | | 0.4147 lbs/min = 2,488 lbs/hr $= \frac{2.488}{4.67} = 0.532$ lbs/hp-hr | |